MONITORING THE WORLD OCEANS FOR HUMAN ACTIVITY USING SMALL SATELLITES

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ABSTRACT

A passive EO small satellite concept was studied under contract to ESA. The human impact on the world oceans is increasingly important in terms of pollution, climate change and sustainable fisheries. Agency Earth science missions have gaps in temporal coverage, which could be filled with a constellation of affordable small satellites providing complementary data sets.

A compact instrument concept is presented that can provide covariance analysis of sea skin temperature and chlorophyll, an indicator of phytoplankton population. This is a key indicator of ocean health and links closely to climate change science.

The “Oracle” instrument is intended to be deployed on small spacecraft to provide sub-daily data sets of ocean colour in 8 bands with a SNR of greater than 400 and a TOA brightness temperature with an uncertainly of no more than 0.5K. The instrument includes simultaneous aerosol optical depth retrieval for atmospheric corrections using an 11 band multi-angle spectro-polarimeter. The paper describes the instrument and the small 80kg spacecraft. The mission is well matched to future iterations of the ESA SCOUT programme which aims to prove this type of new EO concept quickly.

1 INTRODUCTION

The Oracle mission objective is to use a microsatellite, namely the SSTL-42, to retrieve three geophysical parameters simultaneously:

- ocean colour
- sea skin temperature (SST)
- aerosol optical depth (AOD)

Since the advent of the first ocean-colour and thermal sensors (CZCS and AVHRR) it has become clear that these two data streams can be used synergistically to understand the ocean [1], for example, understanding mesoscale processes (fig 1).

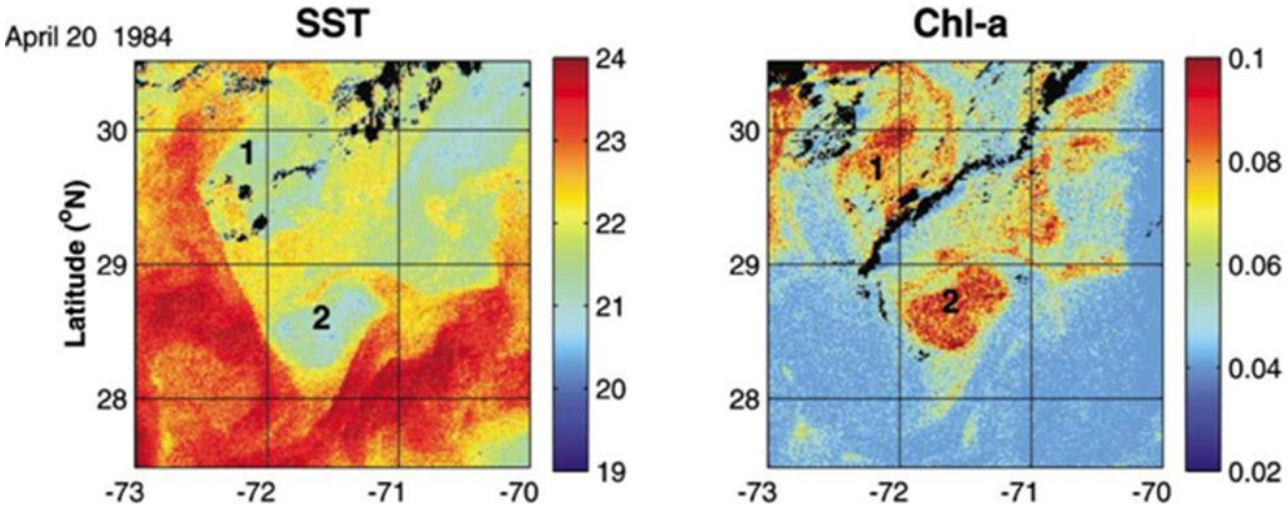

Figure 1. Covariation of mesoscale ocean colour and sea surface temperature in the Sargasso Sea

In addition to using these data streams for exploring mesoscale processes, simultaneous estimates of sea skin temperature and ocean colour can help with retrievals in both data streams, for example:

- Emissivity in turbid waters: Sea skin temperature requires accurate water emissivity estimates. In coastal waters emissivity can change due to increased loading of particles and dissolved substances. In such regions, ocean colour may help improve emissivity estimates [2].
- Satellite phytoplankton type retrievals: It has been demonstrated that SST can improve phytoplankton type retrievals from ocean colour [3-5].

It has also been demonstrated synergistic use of sea skin temperature and ocean colour can improve our understanding of, and retrievals of:

- Satellite primary production: Satellite primary production models require information on phytoplankton biomass and light (from ocean-colour), but also phytoplankton physiology and resources (which can be inferred from SST). It has been demonstrated that SST can help improve primary production estimates [6]. SST is often a good proxy for phytoplankton resources (e.g. nutrients and light).
- Bio-physical feedbacks: Heat budget contribution from phytoplankton can be quantified from both ocean-colour and SST data [7].
- Air-sea gas exchange: Sea skin temperature modulates the transfer of gases (e.g. CO_2) between the ocean and the atmosphere. This relationship has been used together with ocean colour to help quantify the flux of gases between ocean and atmosphere [8].

It is generally accepted that a better ocean colour product is obtained if atmospheric effects from aerosols are removed from the signal. This is usually undertaken by using heritage two-step methods involving an atmospheric model with aerosol data from NIR bands of the ocean colour imagers [9]. There is significant benefit to be had from using multi-angular spectropolarimeters that provide more precise information, particularly regarding absorbing aerosols, which are prevalent over large oceanic areas [10].

Therefore the simultaneous retrieval of ocean colour, SST and AOD leads to a better contextual and accurate measure of marine health.

Furthermore a high retrieval temporal resolution in the order of daily or preferentially sub-daily is likely to lead to a greater understanding of phytoplankton, which is a key indicator of marine health [11].

2 USER NEEDS

Applications of ocean colour such as studying variability in seasonal dynamics (phenology) of phytoplankton are relatively insensitive to accuracy in retrieved products, but depend on relative changes over seasonal and annual cycles. Ocean colour user consultations have highlighted the requirement for long-term, reliable, quality-controlled, stable products. As the length of the time series increases, its value increases [12]. Classical ocean-colour sensors (e.g. SeaWiFS), and recent geostationary sensors (e.g. GOCI), have had 8 bands covering 6 visible and 2 near-infrared parts of the spectrum. These bands have been strategically set to target key water constituents, such as phytoplankton (chlorophyll concentration), sediments and coloured dissolved organic matter.

The GCOS recommends that daily temporal coverage for applications like climate studies is necessary [13]. Sub-daily sampling, e.g. ~every 3 hours, is desirable for exploring diurnal changes in ocean colour, and has the potential to lead to new ocean-colour products, for example, the monitoring of growth and lose rates of phytoplankton, and provide new information on coastal sediment dynamics (e.g. tidal effects).

For SST, there is a strong need for level 3 and 4 data, owing to its use in operational forecasting and for providing single-sensor as well as multiple-sensor, gap-free analyses [14]. There is a strong requirement to provide SST data (direct observations) as well as products that have been adjusted to standard depths (e.g. 20 cm) and times (daily average), reflecting the wide variety of users. Information on diurnal variability is also a requirement for some applications.

Common treads between ocean colour and SST user needs are in their temporal and spatial resolution, with products required typically at daily temporal resolution and around 1km spatial resolution with global coverage. Stability in the data is also very important for climate studies in both cases. Uncertainty specification has been considered important by most ocean-based users [15], for applications like data assimilation. Some examples of user needs in ocean colour and SST are provided by GCOS [13].

For AOD retrieval the 3MI wavebands provide a comprehensive set [16].

A key consideration was in the development of Oracle was sub-daily sampling offered by constellations, which meant that the solution should be capable of scaling for production techniques and the economies of scale that offers.

3 CONOPS

The aim of the mission is to operate for seven years including LEOP and commissioning. Due to the requirement for sub-daily temporal resolution, that is sub-daily global coverage, a constellation of satellites is envisaged. The minimum number of satellites required is dependent on the global coverage requirement. The constellation will be flown at an SSO of 561km that provides a zero-drift orbit, which with different LTANs ensures that the constellation passes over an ROI multiple times daily depending upon the number of satellite, i.e. eight satellites provides eight accesses.

Prior to describing each instrument of the Oracle payload, it is perhaps pertinent to describe the retrieval operation of each instrument as installed in the satellite. The satellite orbits at a constant speed in a constant direction and each of the three instrument simultaneously retrieve data during an imaging session.

3.1 Oracle-C operation

The Oracle-C is nominally a pushframe eight band colour imager (fig 2) that is operated as a pushbroom imager with off-chip TDI of the pixels in each band.

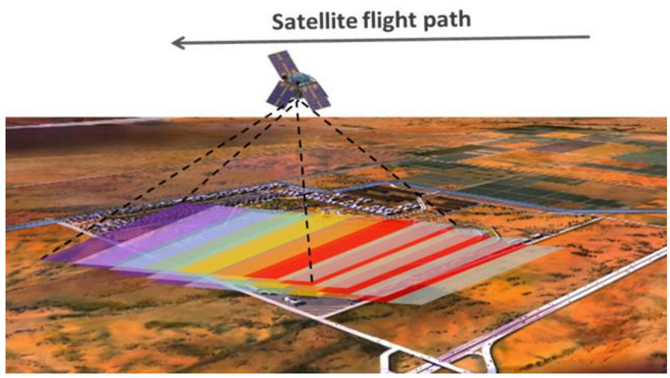

Figure 2. Oracle-C operates as a pushbroom imager

The bands are physically distributed Along Track (ALT).

3.2 Oracle-T operation

The Oracle-T is nominally a pushframe tri-band colour imager (fig 3) that is operated as a pushbroom imager with off-chip TDI of the pixels in each band.

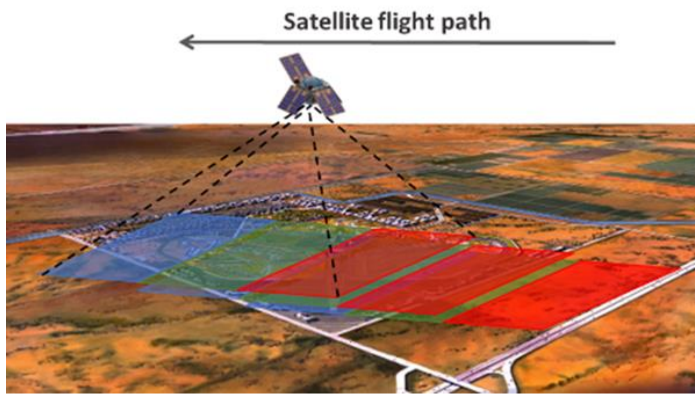

Figure 3. Oracle-T operates as a pushbroom imager

The bands are physically distributed Along Track (ALT).

3.1 Oracle-A operation

The precise measurement of AOD requires the measurement of aerosol size, refractive index and shape. Previous missions, such as POLDER [17], have shown that this can only be achieved if measurements are made of polarised radiances at a range of wavelengths and angles (fig 4).

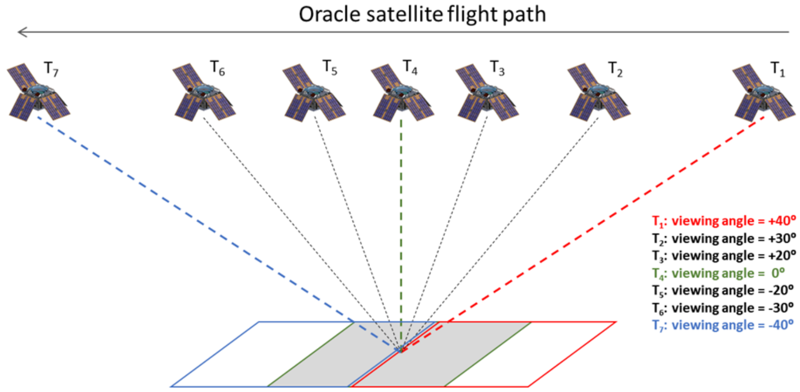

Figure 4. Oracle-A operates as a snapshot imager

The Oracle-A measures the intensity of polarised and non-polarised incident light from the Earth at seven viewing angles. The first view is at an angle ALT of 40º, which is ahead of its current position (T1). This measurement is made at the eleven wavebands (table 3), not included in the Oracle-A retrieval is the 2130nm waveband, as this would require a more complicated detector technology, i.e. cooled MCT, which is cannot be accommodated in the current implementation of the platform being used. Of these eleven wavebands eight have their polarisation state quantified using three different polarisation angles +45º, 0º and -45º. This measurement is repeated at the subsequent six viewing positions (T2-T7) ALT and at the angles of shown (fig 5).

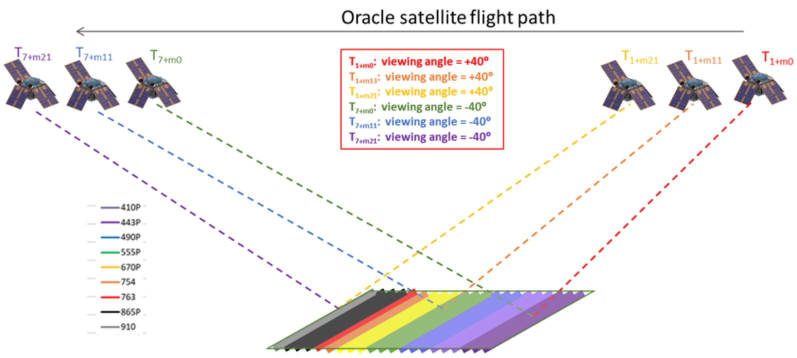

Figure 5. Oracle-A AOD retrieval illustration

It should be noted that at each of the viewing angles there is rotating wheel that like POLDER [17] and 3MI [16] positions each of the filters and filter/polariser pairs in the beam so that either polarised or non-polarised light is focussed onto the 2D area detector. The integration time for each exposure is 0.132 seconds and there are 21 combinations, so that a sample collection at one viewing angles takes 2.77 seconds. All this time the satellite is travelling along its orbital path and covers 21km. So in fact each sample is collected at a slightly different angle, i.e. the first sample is at 40º and the last sample is at 37.8º.

Note that the Oracle-A operation is constant, that is the filter and polariser wheels are constantly rotating and the imager is constantly capturing images. For a particular ACT line only those at the seven viewing angles are relevant. But of course in the ALT direction there is a continuous set of ACT lines of interest adjacent to each other. Thus eventually over a region of 1152km long in the ALT direction 1280 ACT lines are captured each with seven sets viewing angle data at each of the viewing angles.

A nominal imaging session is set at 600 seconds, which is about 4000km, and it is assumed that each orbit is nominally limited to one imaging session because of the vastly different LTANs that are required to achieve several daily accesses. However it is possible to increase the number of imaging sessions at LTANs around 10:30 where the SSTL-42 has the greatest battery re-charge opportunity, potentially to several imaging sessions per orbit.

4 INSTRUMENT DESIGN

The Oracle payload consists of three standalone instruments:

- Oracle-C: an internally calibrated eight-band multi-spectral pushbroom imager with a GSD of 100m operating in the VNIR spectrum from 412nm to 865nm with bands varying from 10nm to 40nm
- Oracle-T: an internally calibrated tri-band multi-spectral pushbroom imager with a GSD of 300m operating in the LWIR spectrum from 9.2um to 12um with each band of 1.0um bandwidth (FHWM)

- Oracle-A: an internally calibrated imager with a GSD of 900nm able to detect polarised light in the VISIR spectrum from 410nm to 1650nm in three polarisation orientations, and at seven viewing angles, operating using the same principles as POLDER [17].

A conscious decision has been taken in the design of the Oracle payload to use three standalone instruments, in order to ensure that if one instrument is subject to a glitch or failure then the other two instruments are still able to function. It should be noted that once the data is egressed to the platform from all three instruments, it is handled by a single dual-redundant payload chain.

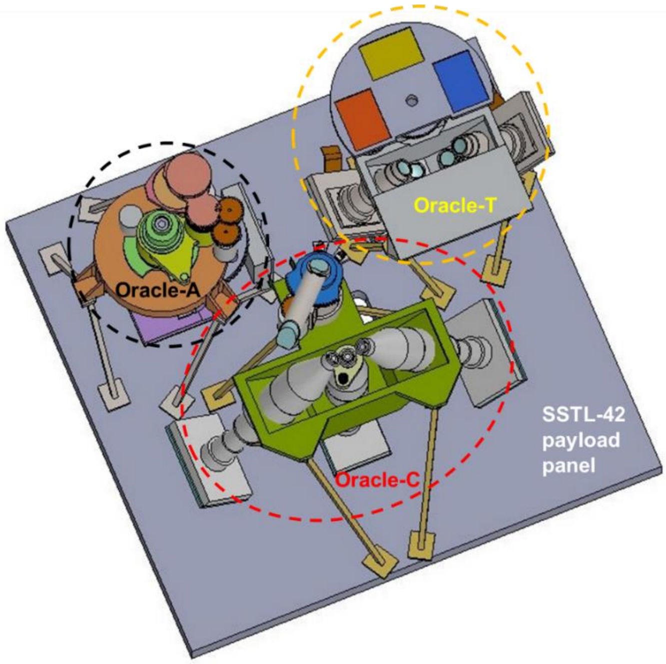

Figure 6. Oracle instrument

Additionally all three sub-instruments are accommodated on the single payload panel of the SSTL-42 (fig 6). In order to achieve a very wide swath of greater than 1000km and maintain the required GSD for the Oracle-C and Oracle-T it has been necessary to develop a solution that overcomes the limitations of currently available COTS detector, namely their format size. These instruments use the technique of combining identical sub-imagers that have a narrower swath and required GSD.

The main parameters for each of the Oracle sub-instruments is summarised in the table below:

Parameter	Oracle-C	Oracle-T	Oracle-A
Focal length (mm)	30.8	31.7	6.2
F-number	3.3	2.0	5.1
ACT pixels	11520	3840	1280
GSD (m)	100	300	900
Swath (km)	1152	1152	1152
Multispectral bands	8	3	11*
Mass (Kg)	8.0	7.8	5.7
Viewing angles	-	-	7

*polarised radiance

Table 1. Oracle characteristics

The mass of each instrument includes the mass of its own calibration device and FEE.

The Oracle payload has been designed using SSTL standard processes, which encompass the best industry practices using COTS CAD packages.

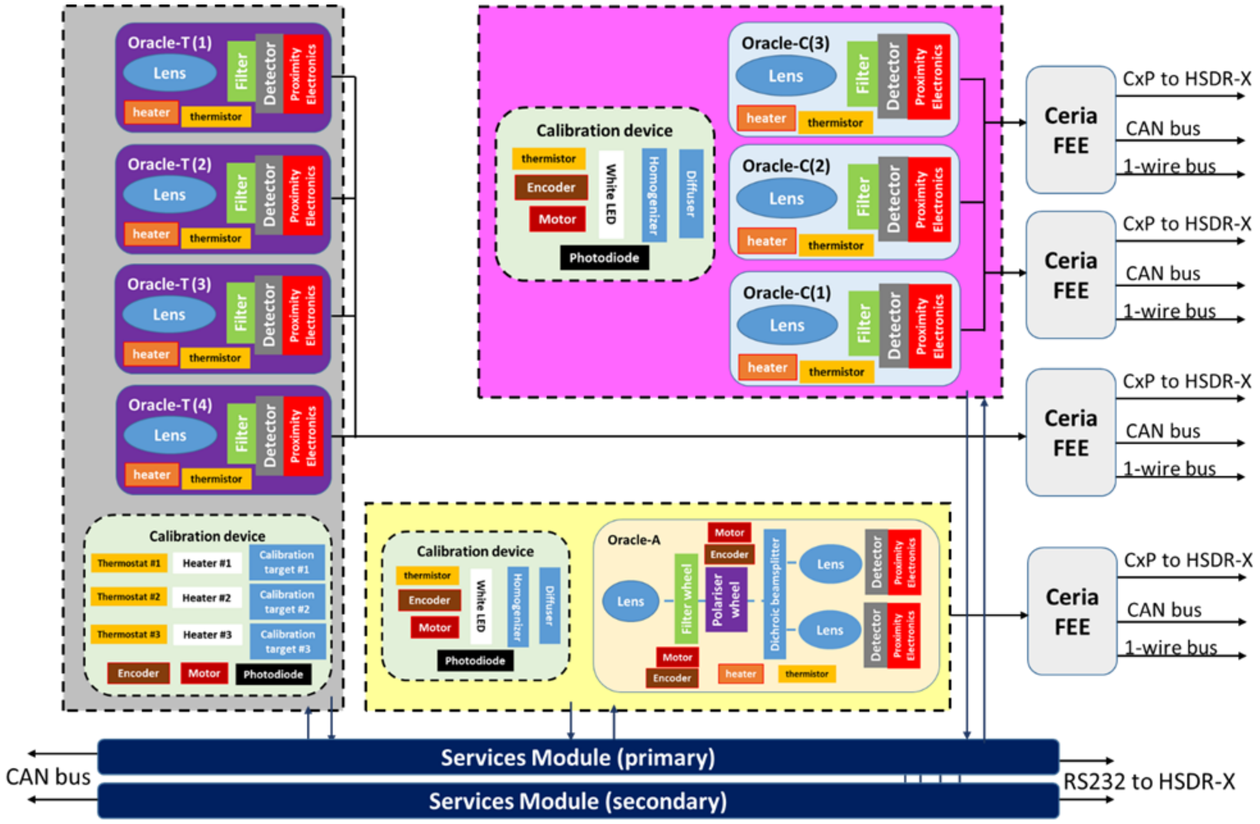

Figure 7. Oracle payload architecture

Both the Ceria Front End Electronics and Services Module are connected to the satellite via the Controller Area Network (CAN) and RS232 for control and CoaxPress (CxP) for relaying imagery. The imagery is sent to the High Speed Data Receiver – X (HSDR-X), which stores the imagery prior to downlink via the X-band transmitter at a speed of at least 160Mbps. The secondary Services Module is cold redundant.

5 INSTRUMENT PERFORMANCE ANALYSIS

5.1 Introduction

The primary parameters of the instruments include:

- Modulation Transfer Function, which indicates the spatial resolution
- Signal to Noise Ratio, which indicates the radiometric performance of a VISIR instrument, i.e. Oracle-C and Oracle-A
- Noise Equivalent Temperature Difference, which indicates the radiometric performance of thermal imaging instruments, i.e. Oracle-T
- Polarisation accuracy of the Oracle-A and Oracle-C

Radiometric accuracy has also been calculated.

5.3 Modulation transfer function

The spatial resolution requirement for the Oracle instrument has been defined in terms of System MTF, which includes the optics, detection chain and degradation due to platform smear.

System MTF	Oracle-C	Oracle-T	Oracle-A
ACT	0.30	0.25	0.40
ALT	0.17	0.12	0.29

Table 2. System MTF of Oracle

The system MTF is greater than the requirement of 0.1 at Nyquist. Motion smear from the platform due to the pushbroom imaging reduces the ALT MTF quite severely.

5.3 Ocean Colour

Assessment of ocean colour retrieval was conducted considering the quality of L2 products. Estimates of uncertainties were made in key ocean colour products (Rrs, Chl, POC and microphytoplankton chl) based on the SNR of Oracle-C, which meets the all minimum requirements [4]. It should be noted that Monte-Carlo simulations were used in order to produce the estimates made herein.

	CWL	Band	SNR	Lref [$Wm^{-2}sr^{-1}um^{-1}$]	Minimum SNR	Lsat [$Wm^{-2}sr^{-1}um^{-1}$]
Ocean colour	412nm	20nm	564	74.14	400	597
	443nm	20nm	626	65.61	400	555
	490nm	20nm	698	51.21	400	576
	555nm	20nm	708	31.49	400	624
	660nm	20nm	655	16.38	400	434
	680nm	10nm	468	15.11	400	417
	745nm	20nm	574	10.33	600	449
	865nm	40nm	560	6.17	600	273

Table 3. Oracle ocean-colour SNR suitability

The minimum requirements of SNR for ocean-colour sensors were recently estimated by Qi et al [18]. It was shown that, once the SNR in the NIR band is greater than 600, which is the minimum required for accurate atmospheric correction [19] then an SNR better than 400 in the visible does not produce a significant reduction in uncertainties in remote-sensing reflectance under typical conditions. However this NIR requirement is not applicable to Oracle-C because the atmospheric correction is conducted using the data from Oracle-A. Therefore the SNR produce by Oracle-C in the visible band is sufficient.

The uncertainties in three ocean colour products (Chl, POC, and Microplankton Chl) have been estimated using the usual standard procedure. The Chl concentration, POC concentration and Microplankton Chl were estimated using ocean colour models:

- the OC3 (SeaWiFS) algorithm [20]
- the Brewin Microplankton Chl algorithm [21]
- the Stramski POC algorithm [22]
- a standard band ratio algorithm used by NASA [23]

The model parameters for OC3, Stramski and Brewin were varied by producing a Gaussian probability distribution in the parameters, assuming 5% uncertainty in model parameters for the OC3 and Stramski models, and taking the uncertainties in model parameters from the Brewin model.

This provided an ensemble of Chl concentration, POC concentration and Microplankton Chl. The standard deviations of these ensembles were divided by the concentrations and multiplied by 100 to estimate the uncertainties in ocean colour products (fig 73).

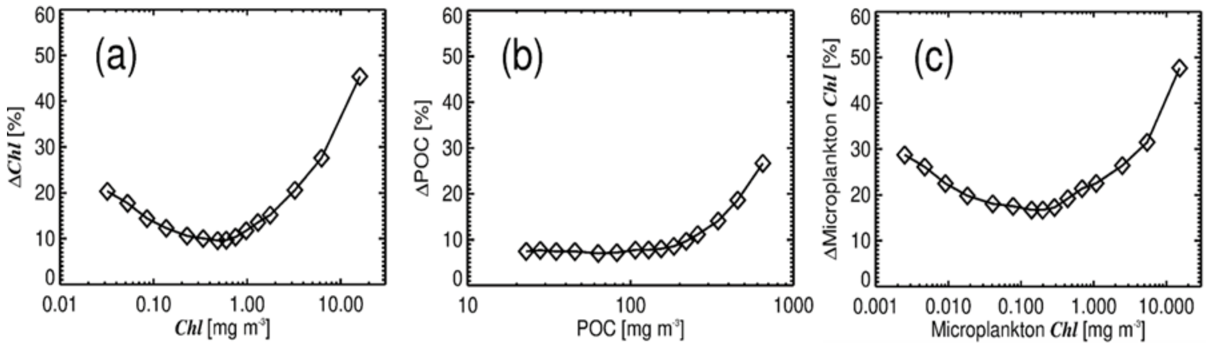

Figure 8. Estimates for product uncertainties for Oracle

It is important to note these simulations are just to provide a qualitative understanding of expected changes in ocean colour product uncertainties using Oracle-C.

5.4 TOA temperature brightness

The Oracle-T TOA radiance brightness temperature is measured by pushbroom imaging with off-chip TDI of 16 stages, which produces a maximum NETD of 0.23K at three different wavebands of 9.2um, 10.6um and 12um, each with a bandwidth of 1um. This simulation is conducted at a scene temperature of 300K.

5.5 Aerosol optical depth

The aerosol optical depth performance of Oracle has not been directly modelled. The requirement and performance goal has been based on the performance of other multi-angle spectropolarimeters. For Oracle the primary goal for the aerosol measurement was to ensure that the instrument met the SNR requirement for 3MI of 200:1.

	CWL [nm]	BWD [nm]	3MI radiance $[Wm^{-2}sr^{-1}um^{-1}]$	SNR
VNIR	410P	20	46.64	264
	443P	20	56.61	317
	490P	20	57.74	346
	555P	20	55.24	358
	670P	20	44.57	331
	763	10	36.11	409
	765	40	36.11	298
	865P	40	28.20	261
	910	20	25.18	141
SWIR	910	20	25.18	287
	1370P	40	10.73	377
	1650P	40	6.80	281

Table 4. Oracle-A SNR values for each spectral band

Using the radiance values of 3MI the SNR values of Oracle-A has been calculated for each band, which matches the 3MI wavebands. The SNR exceeds 200, implying that Oracle-A is capable of providing useful data for the atmospheric correction of the colour data produced by Oracle-C.

5.5 Polarisation sensitivity analysis

The polarisation sensitivity is calculated by the following equation:

$$PS = \frac{(I_p - I_s)}{(I_p + I_s)} \qquad (1)$$

where I_p is the value of the signal of P-plane linearly polarised light and I_s the value of the signal of the S-plane linearly polarised light in the detector.

For the Oracle-C, the modelled values of the signal at the detector for each waveband are used:

band	Ip	Is	PS
412	11079	9684	0.067
443	11760	11201	0.024
490	10483	10247	0.011
555	9076	9046	0.002
660	6222	6222	0.000
680	2650	2615	0.007
745	3338	3208	0.020
865	3328	2939	0.062

Table 5. Modelled polarisation sensitivity of Oracle-C

The polarised optical transmission analysis of the incident beam was conducted in Zemax OpticStudio and applied to the equation 1 for each waveband. The wavebands lie sequentially along track, which means that the extreme wavebands blue and NIR are at the edges of the field ALT, where the polarisation effects are more severe.

The degree of polarisation for Oracle-A has been modelled to be 0.98. The modelled values of the signal at the detector for each "P" waveband are used with the polariser at +45º and -45º:

band	I_p	I_s	P
410	88135	1037	0.977
443	126061	1490	0.977
490	150216	1785	0.977
555	160887	1921	0.977
670	137874	1654	0.977
865	85698	1038	0.976
1370	282350	3490	0.976
1650	187355	2338	0.975

Table 6. Modelled polarisation sensitivity of Oracle-A

The modelling assumes typical tolerances for the polarisers and positioning of the polariser with a typical angular tolerances.

5.6 Radiometric accuracy

Radiometric accuracy is defined as the unknown bias error (difference between the measured and true value) of the values associated to the samples in an image when a stable and spatially uniform scene is imaged

For the Oracle-C the most significant origin of uncertainty is the change in transmission of the optics at the edge of the lens apertures compared to the aperture centres due to polarisation effects. This results in an uncertainty of 13%, which is greater than the requirement. However to be clear this is most marked at the edge of the field, that is in the ACT pixels, and in the ALT, in the blue bands and NIR bands, which are at the extremes of the detector. For pixels in the centre of the ACT field and in the green (555nm) and orange (660nm) bands, the effects of polarisation are less pronounced, although the uncertainty is still 10.2%, which is primarily due to the uncertainty in the calibration device.

For Oracle-T, the most significant origin of uncertainty is the calibration device, which together with the other contributors produces an uncertainty in NETD of 10%, which just over the requirement. At this stage in the development of Oracle, there is uncertainty regarding the control of the calibration devices.

For Oracle-A, the most significant origin of uncertainty is the $\text{Cos}^4\theta$ effect correction from the on-board processing. It may in the end be a better proposition to re-design the Oracle-A lens and move the optical stop form its current position to an internal conjugate position. Oracle-A is also subject to the same uncertainties of the calibration device as Oracle-C. The uncertainty is 15%, which is greater than the requirement.

6 PLATFORM

The "SSTL-42" allows for a payload mass of up to 65Kg with a power provision of 110W and data downlink speed of 160Mbps. The nominal platform already comes with near-full redundancy at the sub-system level and system level - the payload chain is single string due to power, mass and volume constraints.

Figure 9. Oracle instrument accommodated in the SSTL-42

Oracle has been designed to be accommodated in the SSTL-42, having a total mass of 28Kg (including margin), and a maximum power consumption whilst full multi-model imaging of 61W. With current data downlink rate of 160Mbps and the proposed CONOPS a downlink time of 142 seconds is required to download the 22.7Gbits of data.

Each imager of Oracle has a support frame constructed from titanium alloy and is attached to the aluminium alloy payload panel. The frames consist of mounting plates that are connected to bipods. The aim is to maintain the alignment of the imagers to the star trackers and accommodate differential expansion between the structures at the flight temperatures without generating large forces on the imager which would cause internal misalignments between the different cameras. The support frame size provides good conductive isolation of the imager from the spacecraft and it is normal practice to radiatively decouple the imager by enclosing it in multi-layer insulation.

The natural frequencies of the support frame can be reliably predicted and the frame is designed to minimise the coupling of the instrument with the spacecraft response to the launch vibration environment. The overall placement of the imagers align the across track direction of the detector array to be perpendicular to the nominal flight vector.

7 MISSION PROFILE ANALYSIS

In order to model the orbit, Malta was selected as the nominal target area of interest. In order to access Malta eight times daily at evenly spaced intervals during daylight hours, 8 satellites, each in a constant ground track SSO and separated evenly by their Local Time of Ascending Node (LTAN), is proposed. The LTAN for each satellite has been chosen such that a given satellite 'follows' the proceeding satellite half an orbit period apart leading to accesses of a given location (e.g. Malta) on their common ground track being evenly separated by ~48 mins.

Constant ground track SSO occur at particular altitudes, of which 561 km is one for Oracle. At this altitude a satellite orbits the Earth 15 times per day, so its ground track is constant day to day and continues to access a particular location over time. The configuration of the 8 satellites is illustrated below:

Satellite	LTAN	Initial true anomaly
1	11:53:46	0^0
2	12:41:42	180^0
3	13:29:38	0^0
4	14:17:34	180^0
5	15:05:30	0^0
6	15:53:26	180^0
7	16:41:22	0^0
8	17:29:18	180^0

Table 7. Orbit configuration of satellites at 561km constant ground track SSO

Note that the satellites are separated by half an orbital period from each other and to do this they alternate between an initial true anomaly of 0^o and 180^o, i.e. four of them are 180^o apart from the others in orbital phase. This is so that the 8 accesses of Malta are sufficiently close in time that the extremes of daylight access times are not too close to the terminator. A different separation time in LTAN is possible, though this would lead to every satellite being in a different phase in its orbit compared to the others (as well as a different LTAN).

The coverage of the Oracle constellation of eight satellites has been modelled for Malta as the nominal target area, between 70º South and 70º North. However this only provides partial global coverage daily. An addition of another eight-satellite constellation group with shifted LTANs eastwards (or westwards) by an orbit period produces almost complete coverage of the World with eight evenly spaced accesses daily.

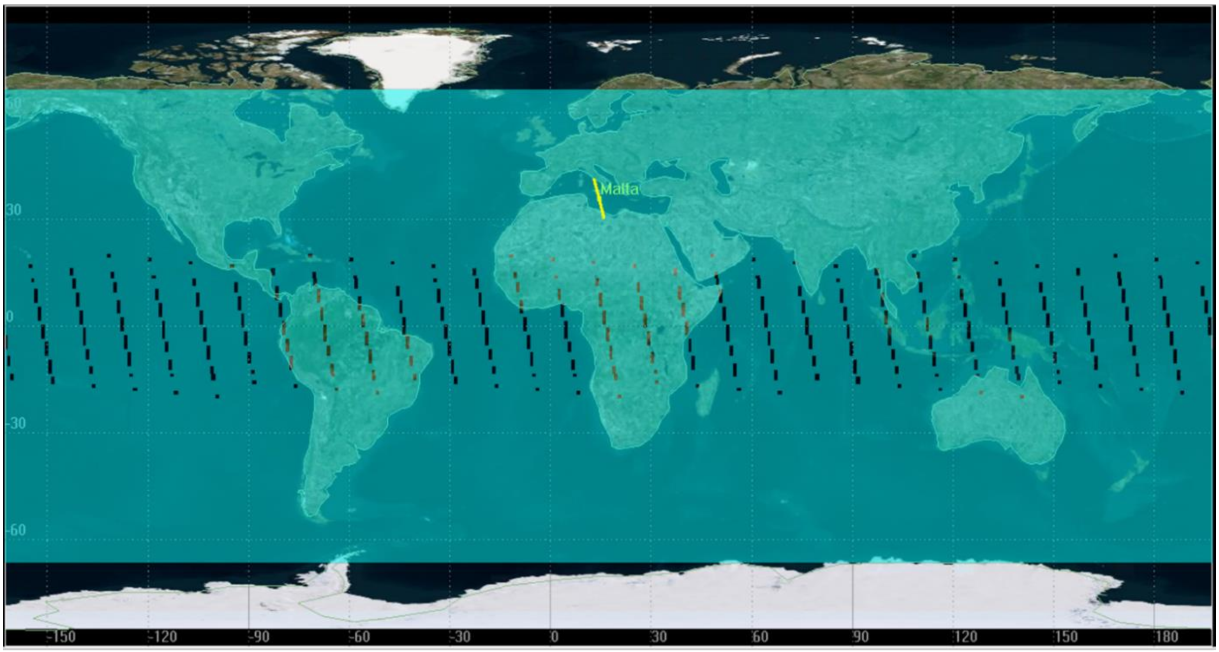

Figure 10. Coverage map for a 16 satellite Oracle constellation

Thus a constellation of sixteen satellites can provides almost globally coverage with eight daily evenly spaced accesses (fig 9). Note that there are some gaps near the equator, which could be covered by off-nadir pointing.

7 CONCLUSION

A preliminary design for Oracle satellite has been completed. At this stage it can be said that, there is further work required to improve the design, notably the improvement of radiometric accuracy, which entails the production and assessment of engineering models of the Oracle internal calibration devices.

The simultaneous retrieval performance of ocean colour and sea skin temperature (with aerosol optical depth to provide atmospheric correction of the colour products) is highly desirable to the User community as it is likely to provide a more complete picture of the effect of human activity on the World’s oceans. A preliminary User assessment of the Oracle instruments indicates that useful data will be retrieved, and the fact that this will be done multiple times per daily globally will open the door to a more detailed understanding of the health of our oceans.

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